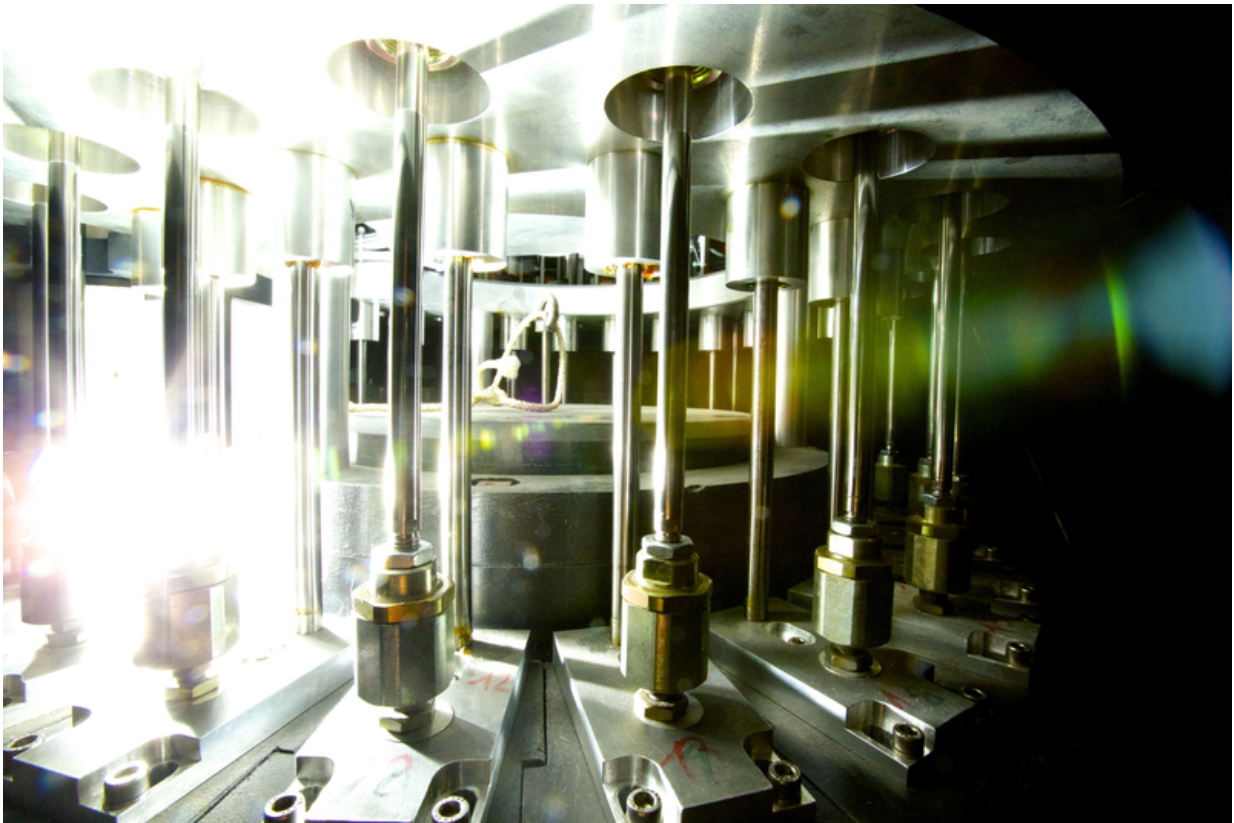


The application of three-axis low energy spectroscopy in quantum physics research

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ThALES. Credit: R. Cubitt, ILL

In modern physics of the past century, understanding the electronic properties and interactions between electrons inside matter has been a major challenge. Electrons are responsible for the chemical link between

atoms and almost all factors that characterise a piece of matter, such as colour, heat transport, conductivity and magnetism. An elementary property of electrons is the spin, and the combination of electronic spins on the atomic level can induce a magnetic moment on certain atoms, which constitute the material. These moments can add up to macroscopic magnetic forces.

As magnetism is the footprint of the interactive behaviour of electrons, studying it on the [atomic level](#) informs us about the collective electronic behaviour in the atomic environment. This can explain macroscopically observed electronic properties, like the temperature dependence of the conductivity.

On the atomic level, magnetic ions are closely packed and thus mutually influence each other, resulting in the adoption of a common magnetic order to minimise their energy balance. A slight perturbation leads to a spin wave, whereby an oscillation of one magnetic moment around its central axis induces oscillating perturbations with a slight phase shift on the atomic neighbours. Spin waves are routinely observed in ordered magnetic materials by inelastic [neutron](#) scattering (INS) on spectrometers at the Institut Laue-Langevin (ILL).

Transitioning from a classical to a quantum magnetic world

The magnetic moment is characterised by its spin number. The larger the spin number, the more appropriate it is to compare the atomic [magnetic moment](#) with a classical magnet. Lowering the spin means accentuating its [quantum](#) properties; exploring the transition into the quantum world, which is fundamentally different from the daily, macroscopic world, is one of the most exciting challenges in solid state physics.

The most cited example is the spin $-1/2$ moments placed in the corner of an equidistant triangle. Due to its quantum nature, one spin can only point upwards or downwards with respect to its local axis. A magnetic exchange between the spin moments, that is antiferromagnetic in nature, forces them to align antiparallel to each other. As a quantum magnet cannot order, rather than adopting one ground state, several [states](#) are equally likely (6 in the case of the triangle), and the spins are in a superpositioned state pointing in several directions at once.

Combining equidistant triangles leads to a two-dimensional network of spins. Its ground state, i.e. the spin arrangement with the lowest possible energy cost, has challenged theorists for decades. In 1973, noble laureate P.W. Anderson proposed a so-called '[quantum spin](#) liquid state,' which is conceptually completely different to ordered magnetic phases. Anderson argued that for a triangular system, it is energetically more favourable for spins to organise into bonds. In these valence bonds, electrons are quantum mechanically 'entangled,' a purely quantum mechanical state. A superposition of a manifold of bond pattern exists in parallel and bonds fluctuate due to a quantum mechanical principle, which imposes zero point motions on the particles. This state is called a Resonant Valence Bond (RVB) state.

Neutron scattering provides experimental proof for the RVB state

Here at ILL, two cold three-axis spectrometers, IN14 and IN12, contributed over decades to the discovery and unravelling of magnetic correlations in classical and non-conventional superconductors, multiferroic crystals and a wide range of low-dimensional, frustrated and quantum magnetic systems. As both instruments dated from the 1980s, they were in need of a complete refurbishment to be able to continue contributing to the scientific progress in these fields. The new IN12

spectrometer's relocation and refurbishment was completed in 2012, and by the end of 2014, the IN14 spectrometer was replaced by its successor, ThALES.

ThALES, Three-Axis instrument for Low Energy Spectroscopy, is a next generation cold neutron three-axis spectrometer that builds on the strengths of its predecessor, IN14, but uses state-of-the-art neutron optics. The ThALES project is a collaboration between ILL and Charles University, Prague, and is financed by the Czech Ministry of Science and Education.

After replacing the IN14, ThALES became the new reference for cold single crystal neutron spectroscopy at a steady state neutron source like the ILL reactor. ThALES has been fully optimised to address the physics of highly correlated electron systems and scientific problems in the field of quantum magnetism. Moreover, the flexibility of the spectrometer has been enhanced through the implementation of various optical elements.

The key aims of ThALES are:

- to increase the overall data collection rate through rebuilding the primary spectrometer's neutron optics;
- to provide a polarised neutron option that is efficient and easy-to-use;
- to extend the incident neutron range towards higher energies, and thus bridge the gap with thermal instruments;
- to be able to use high-field magnets without restrictions of the kinematical range, i.e. under all potential experimental conditions.

ThALES was used to carry out INS measurements in a recent study conducted by a collaboration of scientists, including ILL's Martin Boehm, current co-ordinator of the EU-funded neutron network

SINE2020. The study published in Nature, titled 'Evidence for a spinon Fermi surface in a triangular lattice quantum-spin-liquid candidate,' argued that the triangular-lattice antiferromagnet YbMgGaO_4 has the long sought quantum spin liquid RVB ground state. This study was the first to use neutron scattering as a means of providing [experimental proof](#) for the RVB state.

The experimental effort to discover the RVB ground state has considerably increased since P.W. Anderson suggested that it might explain the phenomenon of superconductivity in a class of materials that show particularly high transition temperatures between a normal conducting and superconducting state. However, providing experimental proof for the existence of the RVB state is very challenging, because while a magnetically ordered system has a clear experimental response, the RVB state is characterised by the absence of a measurable quantity.

Due to the lack of a measurable quantity, the experimental approach of this study, using ThALES, selected indirect experimental proof by deliberately exciting the ground state with neutrons and measuring the dynamic response. According to theoretical expectations, the excited spin liquid behaves 'exotically,' meaning the excited state is explained by spinons with very unusual properties. Spinons can rearrange the distribution of valence bonds and travel throughout the triangular plane with a minimum amount of energy.

In a scattering process between the neutron and the spin liquid, the law of conservation of total momentum imposes the creation of two spin-1/2 spinons in the liquid. This pair of spinons travel in opposite directions with a total amount of energy equalling the loss of neutron energy in the scattering process. Using the ThALES spectrometer, it is possible to trace the direction and energies of the spinons by measuring the direction and energy of the neutron that created the spinon pair. In this way, this study traced a complete dynamical landscape of the spin

quantum liquid in the triangular plane, and compared the measurements with theoretical predictions, which gave strong evidence for the existence of the spin liquid phase in YbMgGaO₄.

This research is important as a quantum spin liquid state of matter is potentially relevant for applications of quantum information. Moreover, experimental identification of a quantum spin liquid state contributes greatly to our understanding of quantum matter.

More information: Yao Shen et al. Evidence for a spinon Fermi surface in a triangular-lattice quantum-spin-liquid candidate, *Nature* (2016). [DOI: 10.1038/nature20614](https://doi.org/10.1038/nature20614)

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